An Ice-Free Arctic?
Opportunities for Computational Science

The authors discuss modeling's role in understanding the ice-ocean system, as well as its importance in predicting the future state of Arctic sea-ice. In doing so, this article presents results from a hierarchy of models of different complexity, their strengths and weaknesses, and how they could help forecast the future state of the ice-ocean system.

A primary strength of 3D general circulation models (GCMs) is how well they simulate the coupled interactions between sea-ice, the land surface, the atmosphere, and the ocean, all of which are essential for understanding the climate system's response to forcing perturbations. However, GCMs have limited spatial and temporal resolution (because of total integration time) and sometimes fail to capture the fundamentally important processes that affect climate variability. Moreover, the computational constraints on large models restrict the number and length of sensitivity experiments.

Component models, on the other hand, use specified forcing at the boundaries, and although they can't study the coupled system's response,

they are easier to interpret and are useful for studying individual forcing parameters. Researchers can also use models of intermediate complexity, such as regional ice-ocean coupled models, to study certain processes in partially coupled modes. Perhaps the best option of all is to use a hierarchy of models—a combination of intermediate-complexity models, process models, and GCMs—to gain a clearer understanding of how multiple processes can affect, say, the high-latitude climate system.

The field of climate variability involves a wide range of spatial and temporal scales. Small spatial-scale processes such as turbulence, mixing, and convection, for example, affect large-scale ice-ocean-atmosphere circulation patterns, which determine the system's basic state, which in turn affects small-scale processes. Small spatial-scale processes also typically operate over shorter timescales. Resolving (or parameterizing) the climate system's smaller-scale features while performing long-term integrations on complex GCMs constitutes the principal challenge for computational scientists interested in the field.

In this article, the authors discuss future projections of the Arctic sea-ice cover from sophisticated General Circulation Model (GCMs), the uncertainties associated with these projections, and how the use of simpler component models can help in the interpretation of complex GCMs.

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ICE-OCEAN MODELING

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This issue's article for the International Polar Year focuses on various methods for modeling ice-ocean interactions. This is timely not just because of the IPY but also because the much publicized shrinking Arctic ice cap and expected changes in climate due to shifts in ocean currents.

The following Web sites highlight different aspects of a changing Arctic from satellite data to model projections and intercomparisons:

- NASA's Scientific Visualization Studio site is a great place to start because it plays movies created from satellite measurements as well as from model projections (http://svs.gsfc.nasa.gov/). To see beautiful animations of sea-ice changes, search for "sea ice" on this site; one of the best depicts the minimum ice concentration from 1979 to 2006 (http://svs.gsfc.nasa.gov/vis/a000000/a003300/a003378/). For a variety of other movies of Arctic data, go to http://svs.gsfc.nasa.gov/search/Keyword/Arctic.html.
- Scientists at the Geophysical Fluid Dynamics Laboratory (GFDL, www.gfdl.noaa.gov) are investigating climate variability and prediction from annual to centennial timescales. You can see one of their state-of-the-art models of the shrinking Arctic ice cap at: www.gfdl.noaa.gov/research/climate/highlights/GFDL_V1N1_gallery.html.
- The US National Center for Atmospheric Research is home to the Community Climate System Model (www.ccsm.ucar.edu), and as the name indicates, the climate community is heavily involved in the model's development. You can find an overview of the model at www.ucar.edu/communications/CCSM and more about high-latitude simula-

tions at www.ccsm.ucar.edu/working_groups/Polar.
- To make more sense of the results of different models worldwide, Lawrence Livermore National Laboratory has established a program to facilitate model comparison (www-pcmdi.llnl.gov/projects/cmip/).

The article in this issue describes two extremes in the hierarchy of models used to investigate ice-ocean interactions—namely, large-scale global models and small-scale ice models. In between these is a class of models called *regional models*, which are typically forced with either real climate data or GCM data at their boundaries and can be run at higher resolution to investigate smaller scale effects, such as local orography, smaller-scale weather forcing effects, and so on. You can find more information on the intercomparison of these arctic regional ice-ocean models at the Arctic Ocean Model Intercomparison Project (AOMIP; http://fish.cims.nyu.edu/project_aomip/overview.html).

The next article in our series dedicated to the IPY will move onto land and provide insights into modeling high-latitude terrestrial vegetation dynamics, once again using a hierarchy of models of varying complexity. Of course, due to space constraints, we can't cover all the relevant topics in this series, and most notable among our omissions is coverage of biogeochemical processes. One of particular relevance for the polar oceans is the carbon cycle in the ocean; recent studies show that the acidification of the ocean due to enhanced carbon dioxide is particularly important in the cold polar waters. This acidification is expected to dissolve the calcium-based shells of small marine organisms, unleashing a major impact on the food chain. Models of these chemical-biological processes are at an early stage of development, although researchers expect that biogeochemistry models will become an integral part of what are presently classified as climate models.

Arctic Sea-Ice

Over the past few decades, the Arctic has witnessed large changes in its land, atmosphere, ice, and ocean components. These changes include a decrease in sea-ice extent and thickness,[1,2] a warming of surface air temperatures,[3] a decrease in the sea-level pressure,[4] deeper penetration of storms in the eastern Arctic,[5] a warming of the North Atlantic drift current and its flow at depth beneath the fresher Arctic surface waters (see Figure 1),[6] the melting of the permafrost,[7] increased river runoff,[8] and changes in vegetation,[9] among others. Of all these changes, the best documented is the decrease of the minimum sea-ice extent as observed by satellite (see Figure 2). Scientists have seen a decrease in September sea-ice extent of 8 percent per decade since the late 1970s,[10] with three minimum ice records broken in the past four years.

All these observations are internally consistent with local feedbacks from the ice, clouds, and the surface energy budget (the balance of energy coming in and then leaving the surface). At high latitudes, the dominant feedback mechanism believed to be responsible for increased local warming is called *ice-albedo feedback*. If the climate warms, the sea-ice in the polar seas retreats, and the fraction of solar radiation absorbed by the ice-ocean system increases (sea-ice reflects most of the incoming solar radiation; the ocean absorbs most of it). This leads to further warming of the ocean surface and the overlying air, further retreat of the sea-ice, further warming, and so on. This positive feedback can cause large and very rapid changes in surface conditions and local climate—early models based on sea-ice albedo feedback alone predicted several

degree changes in the global mean temperature initiated by small changes in radiative forcing.[11]

In the real world (and in more complex models), negative feedback mechanisms damp or delay the climate system's response to changes in forcing. One such mechanism operating at high latitudes is the *cloud-albedo feedback*. When sea-ice retreats, more ocean water is exposed to the atmosphere. This leads to more evaporation (the overlying warmer air can hold more water vapor than the colder atmosphere) and potentially more clouds, which are highly reflective of solar radiation. In effect, we've replaced a highly reflective material at the surface (sea-ice) with an equally reflective surface up in the atmosphere (the clouds), but they don't cancel each other out entirely. Instead, the combined effect of changes in cloud and sea ice has a reduced but still significant effect on top-of-atmosphere (TOA) albedo, which is important to global temperature (see Figure 3). In fact, in a cloudier Arctic, increased longwave radiation reaching the surface can intensify sea-ice melt, especially during the spring.[12]

In the late 1980s and early 1990s, more storms than usual penetrated deep into the eastern Arctic, a phenomena that became part of a trend in the North Atlantic Oscillation (NAO). During a positive NAO phase, storms preferentially move northward in the Icelandic and Barents Seas (rather than across the Atlantic or Baffin Bay), with the sea-level pressure in the northern part of the North Atlantic relatively lower. These storms carry sensible and latent heat north, create wind patterns that blow ice away from the coastlines of the Kara and Laptev Seas,[13] and export thick multiyear ice from the central Arctic through the Fram Strait,[14] which thins the ice in the peripheral seas. The associated heat flux from the relatively warm ocean through the thin ice cover keeps the overlying atmosphere warmer. These storms also result in a greater poleward heat transport (both in the ocean and in the atmosphere), warmer surface air temperature in the eastern Arctic, deeper penetration of North Atlantic drift waters along the continental shelf, less multiyear ice in the central Arctic, and increased precipitation and runoff from the Eurasian continent.

All the feedback mechanisms we mentioned earlier lead to a larger warming signal—called *polar amplification*—in the high latitudes, particularly in the northern hemisphere, which has a perennial sea-ice cover and the potential for a stronger ice-albedo feedback signal. As a result, although climate models predict a global mean warming of 3 to 5 degrees Celsius by the end of the 21st century

Figure 1. Arctic Ocean surface circulation. Red arrows indicate warm Atlantic Ocean currents and blue arrows indicate cold Arctic surface currents. North Atlantic drift waters entering the Arctic west of Svalbard flow counterclockwise at depth (the warm core is at roughly 300 meters) and exit through the Fram Strait (not shown).
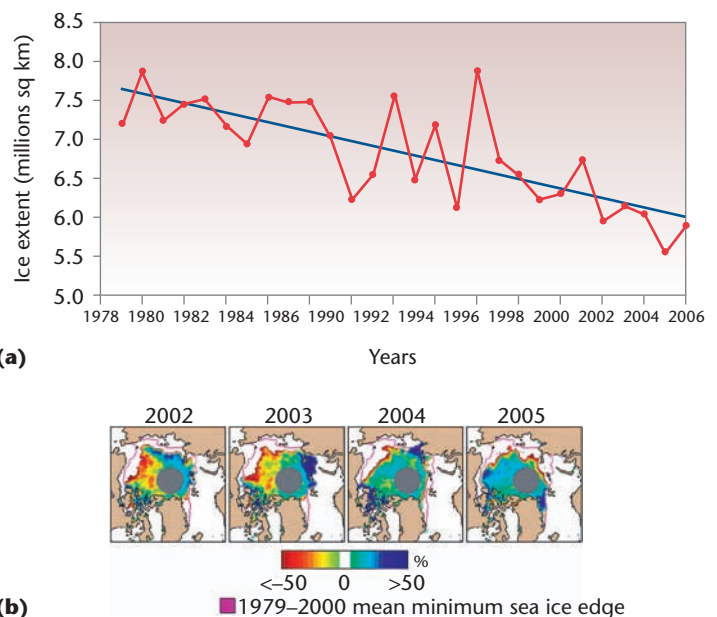

(a)

(b)

Figure 2. Satellite observation. (a) The trend in September sea-ice extent in the Arctic, and (b) sea-ice extent anomalies for (1) 2002, (2) 2003, (3) 2004, and (4) 2005. The pink line represents the mean ice-edge position averaged over the satellite era.

(assuming a continued increase in greenhouse gas[15]), the same models predict a warming of 10 to 15 degrees Celsius and a much reduced sea-ice cover in the Arctic in the same time frame.[16] Because of polar amplification, the Arctic region
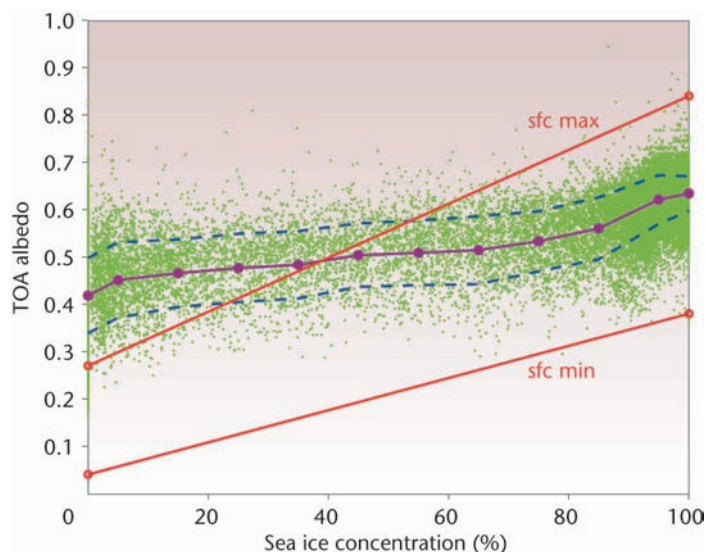
Figure 3. Monthly mean top-of-atmosphere (TOA) albedo (green dots) against northern hemisphere sea-ice concentrations (SICs). Purple dots connected with a line represent area-weighted TOA albedo averages for each 0, 100, and 10 percent bin of SIC. The dashed lines are standard deviations, and the thin red lines connect maximum and minimum observed surface albedo values for both the open ocean and sea-ice, corresponding to the TOA albedo envelope in the absence of an atmosphere. (The TOA albedo is from the Earth Radiation Budget Experiment's [http://asd-www.larc.nasa.gov/erbe/ASDerbe.html] data, and the SICs are from the Hadley Centre's sea-ice and sea surface temperature data set [http://hadobs.metoffice.com].[23])

could be a place where scientists can more clearly separate a warming signal associated with human activity from naturally occurring climate variability. These are among the reasons that climate scientists are interested in monitoring and modeling the high latitudes, and why they do field work in such remote and harsh environments.

The Ice-Ocean System's Mean State

Sea ice and oceans are present in both hemispheres at high latitudes. Yet, the two systems' natures and behaviors are very different.

Sea ice forms when surface waters reach their freezing points (roughly –1.8° Celsius for typical ocean waters), but for this to occur, the surface ocean must be stratified.[17] When seawater cools, it becomes denser—the heavier surface waters sink (*convect*) and mix with deeper waters. In a stratified ocean, the depth to which the water convects is limited to the surface layer, so only the first few tens of meters (roughly 40 meters, for the Arctic) must cool to the freezing point for sea-ice to form. In an unstratified ocean, the entire water column

(roughly 4,000 meters) would need to cool before ice could form on the surface.

In the Arctic, surface stratification mainly comes from the input of fresh water from river runoff. The Arctic Ocean constitutes 2 percent of the Earth's total ocean volume, yet it receives approximately 10 percent of total continental runoff. The cold and relatively fresh surface waters (the mixed layer) sit above an equally cold but somewhat saltier layer of water called the *cold halocline layer* (CHL). Beneath this layer are warmer and saltier waters from the North Atlantic. The CHL's presence in the Arctic buffers the cold surface waters from the warmer Atlantic waters by limiting the ocean heat flux into the mixed layer during the winter growth season, which in turn helps the buildup of a perennial sea-ice cover. Two different mechanisms explain the CHL's formation. In the first, shelf-water advection feeds the cold halocline waters: when ice forms at the beginning of the cold season it rejects salt, making the relatively fresh shelf waters saltier. These waters are advected offshore and find their level of equilibrium between the lighter (fresher) surface waters and the heavier (saltier) Atlantic waters. In the second, deep-ocean convection feeds the cold halocline waters; the relatively fresh shelf waters are advected offshore and remain near the surface (http://psc.apl.washington.edu/HLD/Lomo/Lomonosov.html).

In the Southern Ocean, surface stratification is much weaker and is mainly due to melting ice shelves, melting sea-ice, and the runoff from the continental ice sheet. The mixed layer sits directly atop the warmer and saltier pycnocline waters. In early winter, once the shallower seasonal pycnocline (from the previous summer sea-ice melt) is eliminated when ice grows in fall, further ice formation (and salt release) later in the winter causes convection and entrainment of the warmer sub-pycnocline waters to the surface. This will melt or prevent from forming approximately 1.5 meters of ice each winter.

A Seasonally Ice-Free Arctic

When scientists talk about an ice-free Arctic, they're generally referring to a summer ice-free Arctic Ocean—that is, one that has lost its perennial sea-ice cover, a situation that's sometimes called the *Antarctic analogue*.[18] In winter, no model projects a complete disappearance of the sea-ice cover until at least the end of this century.

In the Arctic Ocean, approximately 1 meter of ice forms each year during winter, 0.7 meters melt during the summer, and an equivalent of 0.3 meters are exported south to the North Atlantic where it melts.

We could achieve a seasonally ice-free Arctic through a sustained increase in sea-ice export out of the Arctic via the Fram Strait,[14] a decline in winter sea-ice production, or an increase in summer sea-ice melt.

Anomalous Ice Export

The mean time sea ice resides in the Arctic is approximately seven years. For the sea-ice export to have a significant impact on the volume of ice remaining in the Arctic, anomalous wind patterns must be maintained for at least this amount of time. However, as we mentioned earlier, a strong negative feedback limits the impact of enhanced sea-ice export on Arctic ice volume.[14]

When export is anomalously high, the volume (or mean thickness) of ice left behind decreases, and the heat lost from the ocean to the atmosphere (and concomitant sea-ice formation) increases. In the late 1980s/early 1990s, researchers observed a trend toward a more positive NAO index, with deeper penetrations of storms in the eastern Arctic and winds blowing the thick multiyear ice from the central Arctic out through the Fram Strait. Some scientists have hypothesized that the very low ice observed in subsequent years is the result of this trend.[3] However, since the mid-1990s, the NAO index hasn't been as positive, yet the system hasn't recovered.

Anomalous Winter Sea-Ice Growth

The typical heat loss from the Arctic Ocean to the atmosphere is 15 Watts per square meter ($W\,m^{-2}$) (equivalent to a 1-meter ice growth over an 8-month growing season). In winter, the dominant factors in the surface heat balance are upwelling and downwelling longwave radiation and the conductive heat flux through the sea ice.[19] On a typical clear-sky day, the net longwave radiation emitted from the surface is approximately 30 W m^{-2}, whereas the net longwave radiative flux drops to almost zero during cloudy skies.

The expected increase in downwelling longwave radiation by 2050, as predicted by the latest generation of GCMs from the International Panel on Climate Change's 4th Assessment (IPCC-AR4) ranges from roughly 10 to 25 W m^{-2}, depending on the model used and the future CO_2 increase scenario considered. This is significantly larger than the same models' global average, which ranges from 3 to 15 W m^{-2}, and of the same order of magnitude as the net heat loss to the atmosphere during the winter months. An increase in the downwelling longwave radiation will result in a warmer surface ice temperature, a reduced temperature gradient from the ice base to its surface, and a reduced winter ice growth. These changes would gradually decrease the winter sea-ice growth over time, if no other feedback mechanisms were present. Of all the IPCC models participating in the 4th assessment that have a realistic seasonal ice extent cycle, 40 percent display this gradual decrease.[20]

Anomalous Summer Sea-Ice Melt

In summer, the main balance in the Artic sea-ice's surface heat budget is between the net shortwave radiation absorbed at the surface, the energy required to melt the sea ice, and to a lesser extent the net longwave radiation lost by the surface.[19] Clouds have a large impact on surface melt as well. Whereas winter clouds have a warming effect (increased downwelling longwave radiation), summer clouds reduce the amount of shortwave radiation that reaches the surface and typically have a cooling effect (the increased downwelling longwave radiation associated with clouds doesn't compensate for the decreased downwelling shortwave radiation[21]). Depending on microphysical properties (such as cloud-particle radius and ice versus liquid), clouds can affect the surface radiation balance differently in winter and summer.[22,23]

How the summer melt will change in response to future greenhouse gas production depends largely on the projected changes in Arctic cloud cover and type. At present, satellite observations show an increase in the melt season by a few weeks, associated with the NAO's more positive phase,[10] and possibly with an increase in the downwelling longwave radiation reaching the surface.[12]

Feedback Mechanisms

Increased ice export, decreased winter growth, and increased summer melt will all result in a gradual change in sea-ice conditions in the Arctic Ocean. Let's examine how slowly varying CO_2 increases in the atmosphere could lead to a rapid decline in Arctic sea-ice volume if we reach certain thresholds in sea-ice thickness or surface ocean temperature and salinity structure.

Dynamic Feedback

Energy input by the wind dissipates due to both bottom friction between the ice base and ocean surface and lateral friction between ice floes rubbing against one another along shear lines. When local convergence is present,[24] ridges form, leading to an increase in the system's potential energy. A thinner sea-ice cover has a lower mechanical strength and deforms more easily (sea-ice compressive and shear strengths are functions of thickness, but sea-ice tensile strength is invariably much lower because the pack ice is a highly fractured material that can't
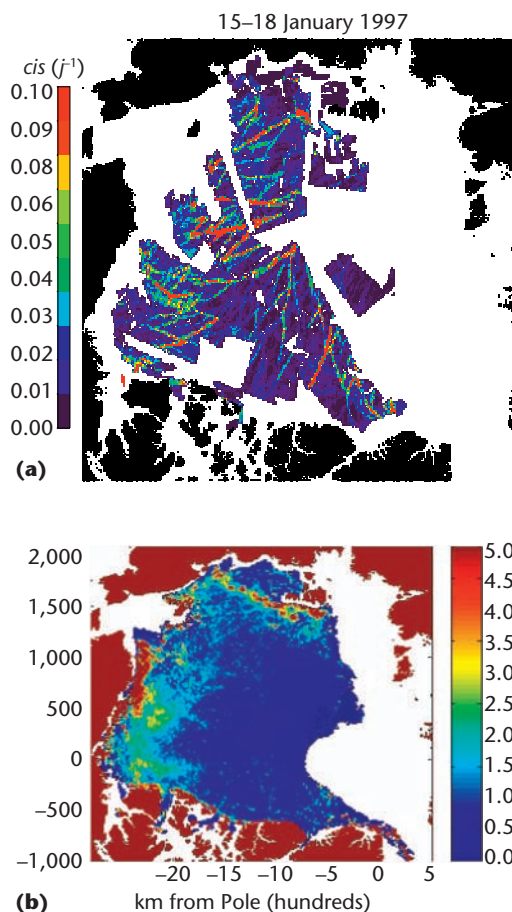
Figure 4. Lead pattern in Arctic sea ice. (a) Shear deformation from the Radarsat Geophysical Processor System (RGPS, www-radar.jpl.nasa.gov/rgps/radarsat.html); (b) mean spatial distribution of open water over the Arctic Ocean for the winters of 1996–1999, derived from RGPS thin ice thickness data. Open water is defined as the ice surface area covered by ice thinner than 10 cm.

sustain large tensile stresses before deforming). Moreover, faster-moving ice yields more mixing at the surface.

Localized high shear deformation can also raise the pycnocline depth (due to Ekman upwelling) and increase turbulent heat fluxes in the surface ocean boundary layer.[25] Figure 4 shows typical lead (a narrow opening in the sea-ice pack that exposes the open ocean) patterns as well as the spatial distribution of leads from three years of Radarsat Geophysical Processor System (RGPS) data. A faster-moving sea-ice cover has a shorter life span in the Arctic (with wind forcing remaining the same), which results in decreased thermodynamic growth.

Loss of the Cold Halocline Layer

As discussed earlier, the CHL buffers the Arctic's cold surface water from the warm Atlantic layer beneath. In the early 1990s, Michael Steele and Timothy Boyd[26] showed that the eastern-central Arctic CHL was weak in 1993 and completely absent in 1995. Without a CHL, the Arctic Ocean assumes characteristics of the Antarctic water column, and with that, presumably an increased ice-ocean heat exchange and a behavior similar to the Antarctic ocean-ice system (that is, a seasonal ice cover). In the late 1990s, the CHL returned.[27] Researchers argued that this excursion was due to a change in the large-scale atmospheric circulation and a concomitant change in river inflow paths along the Eurasian shelf.[28] During that time, the river runoff from Eurasia formed an eastward-flowing coastal current in response to large-scale wind pattern changes (as opposed to flowing off the shelf and along the Lomonosov ridge in the central Arctic).

It's unclear how the CHL will respond to reductions in ice cover. Weakening or loss of the CHL would constitute a large positive feedback mechanism accelerating the decline of Arctic sea-ice cover. To quantify the amount of heat brought up to the surface when sea ice forms, rejects salt, and enables surface convection, Douglas Martinson and Richard Iannuzzi[29] developed a simple bulk model based on the upper ocean's temperature and salinity profile. Douglas Martinson and Michael Steele[18] later calculated (using all available temperature and salinity profiles from the Arctic) the latent ocean heat fluxes that would be released in the event of a CHL loss. The values of heat fluxes ranged from 17 W m^{-2} north of Greenland in the Amundsen Basin to approximately 9 W m^{-2} in the Canadian Basin. Given that the CHL's presence is linked with river runoff paths into the Arctic Ocean and shelf water's hydrographic properties, whether we could lose the CHL over the entire Arctic Ocean at once remains an open question. However, even a partial loss over a limited region of the Arctic would significantly impact the sea-ice cover's thinning.

Ice-Ocean-Albedo Feedback

Another possible mechanism for the rapid decline in Arctic sea-ice cover is linked with *ice-ocean-albedo feedback*. As the sea ice gradually thins due to increased greenhouse gases in the atmosphere, we'll reach a threshold when an anomalously warm year (associated with natural interannual variability) causes a significant increase in open water. This will be followed by increased absorption of solar radiation in the mixed layer and an increase in basal melt along with the usual surface melt. The natural vari-

ability that can trigger these events includes higher than normal atmospheric and oceanic heat fluxes to the Arctic.[20] Observations taken along the Eurasian continental shelf show a pulse-like warming of the Atlantic water circulating cyclonically along the shelf in the Arctic Ocean, and scientists also recorded a few warm events of roughly 1° Celsius in 1990[30] and 2004.[6] Researchers simulated similar warming events with a regional ice-ocean model forced with specified atmospheric forcing.[31]

The Arctic Sea-Ice Cover's Future

The models participating in the IPCC's 4th assessment represent the state of the art in global climate modeling. They incorporate ocean, atmosphere, terrestrial, and sea-ice components as well as the linkages among them.

IPCC-AR4 models consistently exhibit a decrease in Arctic sea-ice cover in response to increasing greenhouse gases, but this retreat ranges widely in its rate and magnitude. Some of this scatter is related to the simulated present-day climate conditions; models with more extensive ice cover in the current climate tend to be less sensitive. An analysis of 14 IPCC-AR4 models shows that the retreat of sea-ice by the mid-21st century is correlated to late 20th century conditions with a correlation coefficient of $R = 0.42$, where R stands for the correlation coefficient between the simulated sea-ice extent in the middle of the 21st century and those of the late 20th century. By the end of the 21st century, however, the correlation degrades to $R = 0.09$, such that, although initial ice conditions are important, other processes dominate. These processes affect climate-feedback strength and can include simulated cloud cover, atmospheric circulation's meridionality (the north–south heat-moisture transport), and the mean and variability of ocean heat transport to the Arctic.

The mechanism for losing perennial sea-ice cover is thermodynamic in nature—that is, it's due to an increased net surface and basal heat budget and melt. For the multimodel ensemble mean, the ice melt for the 2040–2060 average increases over that of the 1980–2000 average by 1.2 meters, whereas the net ice growth increases by 0.2 meters and the ice export decreases by 0.1 meters. This clearly shows that the dominant term for the ensemble mean is sea-ice melt, with ice export and winter growth acting as negative feedbacks. However, the variability in winter growth and ice export is larger, and, for some models, they act as positive feedbacks. Of all the processes that could be responsible for Arctic sea-ice decline, increased summer melt is thus the main player.

Limitation of Current GCMs

We noticed major improvements in Arctic simulation quality from the latest generation of models participating in the IPCC's 4th assessment when compared to the previous generation of models. These include the representation of sea-ice thickness distribution, the simulation of sea-level pressure at high latitude, the atmospheric circulation pattern's meridionality, and precipitation patterns at high latitudes (a discussion of Arctic climate biases associated with the previous generation of GCMs appears elsewhere[32]). Important issues remain, however, and they'll require further attention before we can rely entirely on model predictions of the Arctic's future climate.

Clouds, for example, are inherently difficult to model because of the small-scale nature of the processes that govern their formation. Moreover, Arctic clouds are difficult to measure remotely because distinguishing them from the sea-ice surface in infrared and visible satellite images is difficult. The lack of data and difficulty in collecting it also poses a challenge to the study of Arctic clouds. Fortunately, several cloud detection algorithms specific to the polar regions have been developed recently and validated against ground-based campaigns, while the newly launched satellite programs have much improved capabilities in differentiating clouds from sea ice and quantifying the clouds' microphysical properties (such as, cloud ice and liquid ice water content and particle size).[33]

Measurements conducted during the Surface HEat Budget of the Arctic (SHEBA; http://sheba.apl.washington.edu) experiment showed that liquid water dominates cloud water content over the ice phase in summer, and even winter clouds contain significant amounts of liquid water.[21] Moreover, liquid clouds reflect more shortwave radiation whereas ice clouds are relatively more transparent. The model parameterizations that researchers use to decide whether a cloud is liquid or solid are simple and often based on relatively few field campaigns that aren't always applicable to Arctic conditions. Figure 5 shows the partitioning between liquid and ice in the Arctic from SHEBA observations and three coupled models participating in the IPCC's 4th assessment report. Models with the largest liquid water content show the smallest downwelling short-wave flux during the summer, which is partly compensated for with an increased longwave flux. During the winter months, models with liquid-dominated clouds have higher downwelling longwave radiation compare to the models with ice-dominated clouds.

Another small-scale process that isn't well resolved in current GCMs is linked with determin-
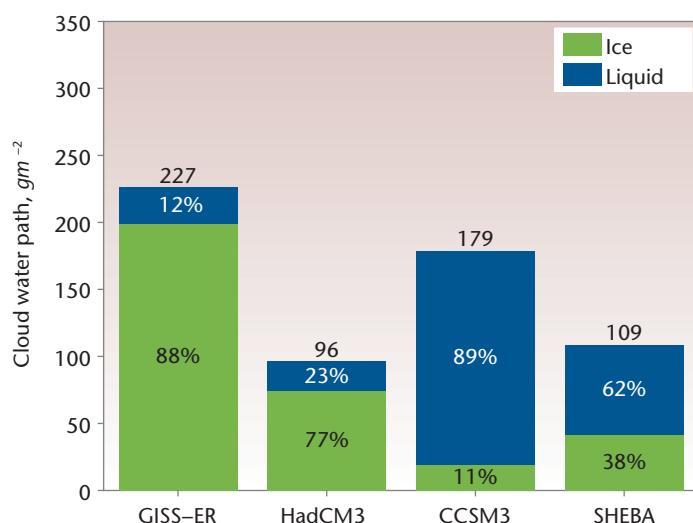
Figure 5. Liquid vs. ice clouds. In comparing the May–September cloud ice vs. liquid water paths from SHEBA's ground-based observations and the GISS-ER, HadCM3, and CCSM3 models, we see a dominance of liquid water clouds in summer, which is sometimes underestimated in some models. The data are averaged from 1959–1998; the numbers above each bar indicate the total cloud water paths (g m⁻²), and the percentages show the partitioning into liquid and ice phases.

ing the upper ocean's vertical structure—in particular, the CHL. GCMs often have problems when resolving the sharp salinity gradients at the base of the mixed layer; instead, they tend to produce saltier surface waters and fresher pycnocline waters, which results in a warm Atlantic layer that isn't buffered from the surface. However, the warm Atlantic layer is often deeper than observed because of the upper water column's salinity structure (see Figure 6). The two effects compensate for each other, often giving realistic sea-ice heat and mass balance. Whether the variability around the mean or the response in a changing climate is realistic remains an open question.

A Simple Modeling Approach

To separate the effect of anomalous atmospheric circulation, increases in the downwelling longwave radiation associated with increased greenhouse gas, and the loss of the CHL in creating a summer ice-free Arctic, we can use a simple stand-alone viscous plastic sea-ice model coupled to a slab ocean and atmospheric energy balance model (a detailed description of the model appears elsewhere[35]). To this end, we ran the model continuously with 1989 wind forcing, a year that had an anomalously high NAO index and sea-ice export; with an increased

downwelling longwave radiation of 20 W m⁻², a typical value simulated by IPCC-AR4 models for 2050; and with a specified ocean heat flux of 20 W m⁻², mimicking the loss of the CHL in the Arctic Ocean. Figure 7 shows a present-day climate simulation. We forced the model run with atmospheric forcing fields for the 1949–2005 time period. In our sensitivity studies, we modified only one forcing field at a time; the other fields remained the same as for the present climate run. In all cases, we used a 10-year mean sea-ice thickness field, calculated from the past 10 years of a 50-year run.

The main features of the present-day climate stand-alone model simulation include thicker ice north of the Canadian Arctic Archipelago (5 to 6 meters) and thinner ice along the Eurasian Basin (1 meter), in good agreement with observations from submarine and satellite altimeter estimates (http://nsidc.org). This sea-ice thickness pattern is due to the dominant winter winds that tend to push ice from the Eurasian continent toward North America as well as the longer life span of sea ice caught in the Beaufort Gyre. The asymmetry in ice thickness is particularly interesting: ice is thicker in the Beaufort Gyre than in the Lincoln Sea (north of Greenland) because of the advection by the Beaufort Gyre of thick multiyear ice westward in front of the Canadian coastline.

When forcing the model with continuous 1989 wind forcing (and keeping everything else the same), the steady state response (achieved after seven years) results in a change in sea-ice thickness, with thinner ice primarily in the East Siberian Sea and the Beaufort Gyre (see Figure 7c). The export of thick multiyear ice from the Lincoln Sea is also clearly visible in the Fram Strait and along the East Greenland coastline. In contrast, the simulation with increased downwelling longwave radiation results in much thinner ice over the entire Arctic Ocean (see Figure 7b). Of the three effects that scientists believe have the biggest effect on sea-ice cover, the loss of the CHL has the biggest impact because it reduces winter ice growth and contributes to a thinner end-of-winter sea-ice thickness that's more prone to substantial summer melt.

The timescale associated with the decline of sea-ice cover in these simulations also differs. Changes in the longwave forcing are gradual and occur over longer timescales than the ice-surface-ocean system's steady-state response (roughly seven to eight years). The sea-ice cover's response in this simulation is therefore in equilibrium with the forcing. On the other hand, both the changes in large-scale atmospheric circulation and in the CHL can occur

on much shorter timescales, so the ice-surface-ocean response time governs the system's response, which in turn leads to rapid changes in sea-ice conditions. For this reason, while the magnitude of the surface forcing for both the increased downwelling longwave radiation and the loss of the CHL is of the same order of magnitude, a loss of the CHL could lead to a much more rapid decline of the sea-ice cover.

The study of polar oceans, sea ice, and the high-latitude climate relies heavily on regional models and GCMs that incorporate several critical Earth system components. Climate models suggest a transition to ice-free Arctic conditions in the summer in the near future (in 50 to 100 years). This represents an unprecedented change in the Arctic climate, with potentially far-reaching effects.

Fortunately, several institutions including national research centers and universities have groups of researchers working on the development, numerical implementation, and coupling of new and improved climate models. These group efforts provide a unique opportunity for scientists in the computational sciences to tackle important climate issues in a stimulating multidisciplinary research environment.
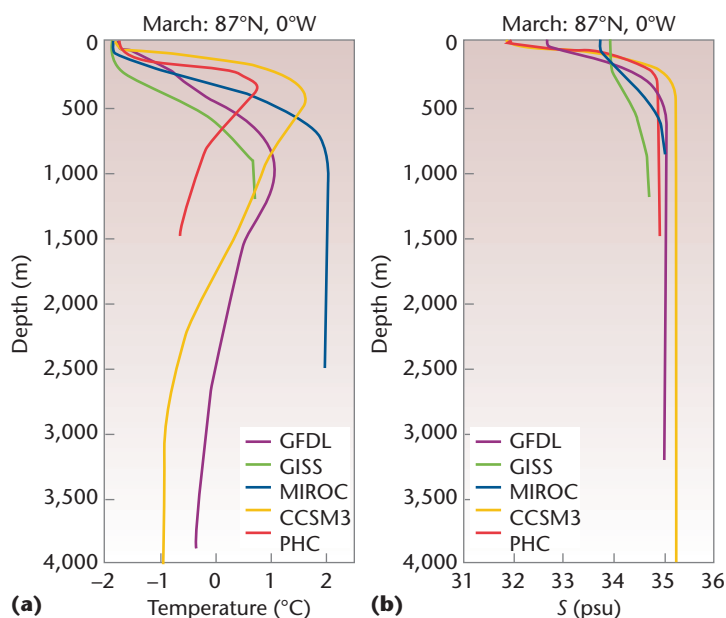

(a)

(b)

Figure 6. Vertical ocean temperature and salinity structure. Four models give different (a) simulated March temperatures and (b) vertical salinity profiles. Of particular interest is the fact that most models have a reduced stratification in the upper ocean and a warm Atlantic layer deeper than observed. The exception is CCSM3, which has a good representation of surface stratification; however, it shows Atlantic waters as 1° Celsius too warm and somewhat saltier.

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(a)
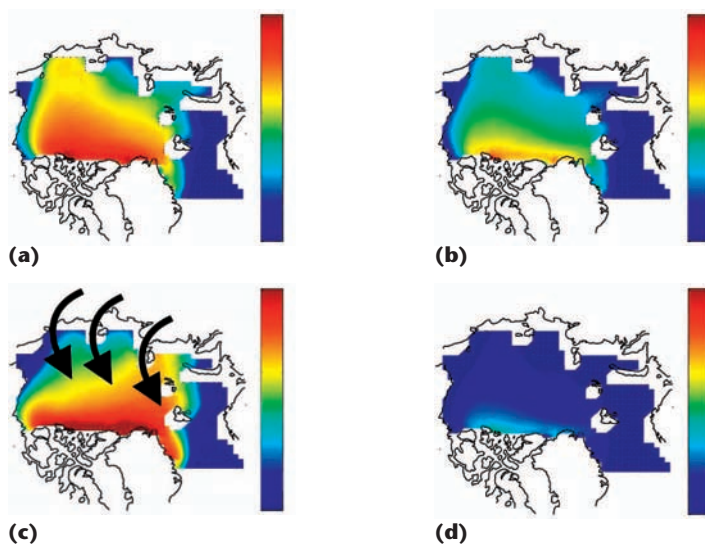
(b)

(c)

(d)

Figure 7. Sensitivity studies using the stand-alone model. We simulated the 10-year mean September sea-ice thickness distribution from a stand-alone granular sea-ice model forced with (a) climatological forcing, (b) increased downwelling longwave radiation, (c) continuous daily varying 1989 wind forcing, and (d) an increased ocean heat flux (17 W m⁻²). The black arrows show the eastern Arctic's dominant winter wind pattern in 1989.

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